LANDING SITE TARGETING AND CONSTRAINTS FOR EXOMARS 2016 MISSION

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ABSTRACT

The Exomars program, led by the European Space Agency and with Thales Alenia Space Italia as prime contractor, foresees two missions: the first, led by ESA, to be launched in 2016, consisting of an Orbiter plus an Entry, Descent and Landing Demonstrator and the second, led by NASA, with a launch date in 2018.

For the 2016 mission scenario, the design of the Entry, Descent and Landing for 2.4 m, 600 kg demonstration module will be under TAS-I responsibility, while for the 2018 mission scenario a European Rover Module will be hosted on a landing platform together with the American Rover, with EDL design led by Jet Propulsion Laboratory (JPL).

Selection of the 2016 AND 2018 landing sites will therefore undergo two separate and distinct processes. This paper presents the approach followed by TAS-I for the identification of the landing site targeting strategy and EDL risk assessment of the EDM-2016 Exomars Mission.

The specific need to harmonize the final science orbit as well as the execution of a successful EDL demonstration poses several limitations to the flexibility of the mission, owing to launchability constraint (mass). The process for identifying a suitable landing site has therefore undergone some dedicated technical assessment, based on the analyses run in Phase B1 of the project and on the knowledge acquired during these past years of Mars observation. The Meridiani region has been selected as a reference landing site mainly for the reason of being well known and widely covered by several observations from past orbiters (MGS, Odyssey, Mars Express, MRO) as well as by the in-situ observations of the MER-B (Opportunity) rover.

The analysis of the requirements for EDM, as well as the identification of specific design constraints, is being considered in parallel to the process of analyzing, characterizing and certifying the landing ellipse features and hazards through a detailed process of engineering analysis of the target site in terms of slopes, craters, rock abundance, thermal properties as well as atmospheric characteristics affecting the whole EDL phase.

In this paper, the methodology for hazard identification and EDL mission success analysis are presented, as a result of current industrial activities in preparation of the System Preliminary Design Review (PDR) that is planned to be held by the end of the year.

1 EXOMARS PROGRAM OBJECTIVES AND COMPONENTS

The ExoMars Program will demonstrate key flight and in situ enabling technologies in support of the future European exploration missions, as outlined in the Aurora Declaration and will pursue fundamental scientific investigations.
The objectives of the ExoMars Program will be pursued as part of a broad cooperation with NASA that will build towards a cooperative Mars sample return mission in the following decades. Two missions are foreseen within the ExoMars Program for the 2016 and 2018 launch opportunities to Mars.

1.1 The Exomars-2016 Mission

The 2016 mission is an ESA led mission that will be launched by a NASA supplied launcher. ESA will supply a Spacecraft Composite in terms of a Mars Orbiter that will carry an Entry, Descent and Landing Demonstrator. Scientific instruments will be accommodated on the ExoMars Orbiter to support the search and localization of Methane sources on Mars.

The 2016 Mission Objectives are:

- Provide Europe with the required technologies for successful entry descent and landing of a payload on the surface of Mars
- Perform investigation on the Martian atmospheric trace gases and their sources
- Ensure communications capability for the 2018 rovers as well as any other international asset on the surface of Mars

The 2016 Mission Components are:

- ESA provided S/C Composite made up of:
  - Entry Descent & Landing Demonstrator Module (EDM)
  - Orbiter Module (OM)

- NASA provided Launch vehicle

1.2 The Exomars 2018 mission

The 2018 mission is a NASA-led mission with the contribution of a 300 kg Rover by ESA. The ESA Rover will be accommodated on a Sky Crane like descent stage and will share the journey with a NASA supplied Rover. Both rovers will arrive at the same site on Mars and start independent surface missions after successful landing and egress from the landing platform.

The 2018 Mission Objectives for the ESA provided Rover are:

- Demonstrate surface mobility
- Access to the sub-surface to acquire samples
- Sample preparation and distribution for analyses by scientific instruments
- Search for signs of past and present life on Mars
- Investigation of the water/geochemical environment as a function of depth in the shallow sub-surface.

The 2018 Mission Components are:

- NASA Spacecraft, MSL-like descent system
- NASA Mars Astrobiology Explorer-Casher scientific rover (MAX-C)
- ESA ExoMars Rover (EXM-R)
- Launch vehicle provided by NASA.

2 EXOMARS 2016 MISSION

2.1 Overall Mission Phases

This section provides a quick summary of the envisaged phases of the Exomars 2016 mission.

Launch: the launch of the spacecraft composite, illustrated in Fig. 1, will take place with an American launcher vehicle, with an allocated 21-days launch window opening in January 2016.

Early operation phase & Spacecraft composite checkout: immediately after separation from the LV upper stage the composite spacecraft will perform all the operations required for sun acquisition and power generation, telemetry acquisition by ground control and stabilization of the attitude. The deployment of the High Gain Antenna (HGA) occurs also during these early operations. A first correction maneuver will be implemented within 7 days from launch to in order to correct the launcher injection errors. Finally, this phase will include a complete spacecraft composite checkout including the science payload.

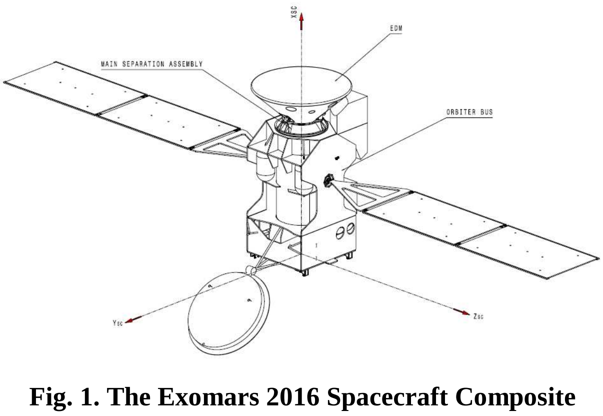

Fig. 1. The Exomars 2016 Spacecraft Composite

Interplanetary cruise: the Type II transfer to Mars has a duration of about 9 months and includes a sizeable Deep Space Maneuver (DSM) in order to reduce the ΔV required for the Mars Orbit Insertion (MOI). Three Trim Correction Maneuvers (TCM) will be carried out during cruise in order to ensure an appropriate targeting of the EDM towards the planned landing site in Meridiani Planum.

EDM Separation & Orbiter deflection maneuver: the composite will reach Mars in a hyperbolic approach trajectory, corresponding to targeting the landing site with direct-entry. Three days before entry the EDM will be released from the Orbiter with the adequate spin rate such as to stabilize its attitude for the entry. Twelve hours after the release the Orbiter will perform a deflection maneuver raising the pericentre of the incoming hyperbola in order to avoid collision and to achieve the adequate conditions to perform the capture maneuver. The Orbiter will perform continuous coverage of the EDM in order to receive the essential data related to EDL events for subsequent downloading to Earth.

EDM Exo-atmospheric coast, entry, descent and landing and Surface phase: the EDM will coast from the release point to the atmosphere entry point and then perform Entry, Descent & Landing (EDL) through the atmospheric flight in order to reach the target landing site. Essential telemetry will be sent to the Orbiter throughout the entire coast and EDL phases. During the surface phase all EDL and surface payload data will be sent to the Orbiter.

OM Mars Orbit Insertion (MOI): will be implemented during the closest approach to Mars with the full thrust configuration of the propulsion system: main engine and the reaction control thrusters in OFF modulation. The target of this maneuver is to reach the nominal 4-sols Mars capture orbit. During MOI the spacecraft must be able to control its attitude in order to thrust in the direction opposite to the instantaneous velocity and to maintain the communications link with the EDM.

Mars capture orbit phase: the Orbiter will perform two revolutions in the 4-sols orbit in order to establish communication with the landed part of the EDM demonstrator during the pericentre passes. The objective is to uplink any information of the EDL phase that may still be in the lander and/or the results of the science experiments and relay this to Earth. This phase also includes the operations and maneuvers that the Orbiter must carry out in preparation for the next aerobraking phase. MOI will change the inclination of the orbit to reach the 74 degrees required for the final science orbit. Then at the next pericentre a tangential maneuver will be performed to lower the apoapsis such that the achieved orbit has the desired apoapsis altitude to perform aerobraking. Nominally this orbit corresponds to a 1-sol orbit with an apoapsis altitude of about 33600 km.

Aerobraking phase: during the aerobraking the apoapsis of the orbit is reduced gradually in order to reach the altitude of the science circular orbit. The aerobraking will be carried out in approx. 6-9 months depending on the aerothermal loads allowed by the spacecraft. This period of time accounts for the required walk-in and walk-out maneuvers. This phase ends with the pericentre raising burn that finally circularizes the Mars orbit.

Mars Orbital Science Phase: the science observations of the Orbiter will take place in this phase for about 1 Mars year. The period of the circular orbit will have to be chosen in order to ensure that the node drift is such that the EDL phase for the following Mars landing mission launched in 2018 is covered by the Orbiter.

Mars Relay Phase: along with other potential NASA Relay Orbiters such as MAVEN, MRO or Odyssey, the ESA EXM Orbiter will be available to provide data relay coverage to the ESA and NASA Mars surface mission launched in 2018 and whose current tentative arrival date to Mars is 2019-01-14.

2.2 EDL mission profile: Meridiani area targeting

The design is performed aiming to land in the Meridiani area, with a target requirement of 50 km x 7.5 km accuracy (semi-major axes).
Specifically the following mission profile applies:

- Arrival at a fixed date (16-Oct-2016) with direct entry from hyperbolic approach and prograde entry in daylight. Hyperbolic excess velocity 3.256 to 3.463 km/s
- Separation from Orbiter Module oriented at EIP attitude with a Main Separation Mechanism providing both axial relative separation rate of 0.3 m/s and stabilization spin rate of 2.5 RPM at the same time
- Entry 3 days after arrival (19-Oct-2016) with implementation of hibernation phase to preserve energy, with entry velocities (co-rotating) raised to 5.70÷5.83 km/s

Tab. 1. Exomars 2016 Arrival and EIP conditions

Event		LW Open	LW Close
Release	Epoch (UTC)	2016-10-16 15:48	2016-10-16 16:01
	Radius [km]	861723	913741
	Delta-V EDM [m/s]	0.251	0.253
	Delta-V Orb [m/s]	0.049	0.047
	SAA [deg]	107.23	104.73
	EAA [deg]	143.39	137.09
EDM Entry	Epoch (UTC)	2016-10-19 15:48	2016-10-19 16:01
	a [km]	-4039.56	-3571.38
	e	1.84465	1.95576
	i [deg]	27.19	34.05
	RAAN [deg]	316.80	320.84
	AOP [deg]	188.42	187.27
	True Anomaly [deg]	-17.49	-17.20
	Radius [km]	3517.515	3517.515
	Altitude [km]	120	120
	Longitude [deg]	-17.28	-16.57
	Latitude [deg]	4.13	5.54
	Relative Velocity [km/s]	5.69601	5.82781
	FPA [deg]	-11.80	-11.80
	Azimuth [deg]	118.06	125.03
	LST [hh:mm]	13:31	13:47
	SAA [deg]	105.80	103.45
	EAA [deg]	142.16	136.08
	Hyperbolic Velocity [km/s]	3.25611	3.46296
	Right ascension [deg]	-160.23	-156.83
	Declination [deg]	-24.59	-30.90

The values on the left column report the conditions at the start of launch window, the values on the right column the conditions at the end of launch window. Owing to the higher entry velocity, 5.83 km/s, the close of launch window represents the sizing case for EDL

- Implementation of a single parachute (Disk-Gap-Band Huyghens type) with supersonic deployment and deceleration to subsonic terminal velocities,.
- Implementation of 3 clusters of 3 PWM engines each, directly mounted on the landed Surface Platform
- EDM sub-modules release strategy with a separation operated at Back Shell/Front Shield and at Backshell under parachute/Surface Platform
- Implementation of the active deceleration strategy dictated by the configuration of the propulsion system as well as by the introduction of crushable structures for impact load attenuation for a drop altitude of about 1.5 m

A full revision of the operational profile with respect to previous Exomars mission design, based on retrograde entries and release from orbit, required relevant changes in the driving constraints for the computation of the entry corridors and the definition of the operational sequence. The basic results for targeting EDL in Meridiani area starting from arrival conditions reported in Tab. 1 can be summarized as follows.

- Entry occurs in daylight with a posigrade entry type
- At launch window start the arrival hyperbolic excess velocity is 3.256 km/s, corresponding to

5.912 km/s inertial velocity at the conventional Entry Interface Point of radius 3517.515 km.

- At launch window end the arrival hyperbolic excess velocity is 3.463 km/s, corresponding to 6.029 km/s inertial velocity at the conventional Entry Interface Point, conventionally identified at radial distance of 3517.515 km[1].

The launch window close presents therefore the sizing case for thermal and mechanical loading owing to the largest entry velocity. In other words, fixing the entry corridor constraints, for the launch window close the corridors are expected to be slightly narrower.

It is noticed from the tables that the entry heading is particularly large, 118°÷125° from North, that is posing some relevant challenges in the placement of the landing ellipses. Owing to morphology of the landing area an eastwards entry heading (close to 90° as for MER-B) would be more suitable and would allow major flexibility for the placement of the landing ellipse. The basic constraint in the identification of optimal approach hyperbolas is related to the need for implementing an Inclination Change Maneuver (ICM) in order to place the OM in the required inclination of 74° for science orbit, following the 8-sol coverage of the EDM surface mission.

Tab. 2. Comparison of Exomars EDM 2016 to MER-B Opportunity Mission

Data	**Exomars EDM 2016**	**MER-B Opportunity**
Entry date	**19/10/2016**	**25/01/2004**
Season	Late Summer	Winter
Landing site	Meridiani	Meridiani
Landing time (GST)	19-Oct-16 03:48 PM	25-Jan-04 04.55 AM
EIP Time (GST) (Entry beginning)	19-Oct-16 03:48 PM	25-Jan-04 04.45 AM
Mars Solar Longitude (LS)	244.7	338.99
Local True Solar Time (LTST) at entry	13:03	12:08:00
Local True Solar Time (LTST) at landing	14:22 - 14:35	13:23:00
Latitude at EIP	4.13N - 5.54N	4.1S
Longitude at EIP	17.3W - 16.6W	18.95W
Latitude at Landing	1.9S	-2.06N
Longitude at Landing	6.1W	354.01E
Landing Altitude /MOLA [km]	-1.44	-1.44
Entry type	posigrade	posigrade
Entry point [km]	121.5	125.92
Entry velocity (inertial) [m/s]	5912 - 6029	5720
Entry velocity (relative) (Co-Rotating) [m/s]	5663 - 5779	5480
Entry FPA (inertial) [deg]	Corridor	-11.47
Entry heading [deg]	118 - 125	83
Diameter [m]	2.4	2.65
Nose Radius [m]	0.6	0.66
Entry Mass [kg]	600	832.2
Ref Ballistic Factor [kg/m2]	77.86	88.88
Parachute diameter [m]	12	15.09
Parachute drag	0.4	0.4
Nominal parachute opening Mach	1.95	1.86
Nominal Parachute opening Dyn.P [Pa]	783	747
Nominal Parachute opening Altitude [km]	10.1	8.7
Nominal Parachute opening FPA	-22.8	-26.54
Heat Shield jettison time/parachute	40 s	20 s
HS jettison Mach	0.4	0.49
Peak Laminar heating (kW/m^2)	602	422
Total heat load (MJ/m^2)	36.87	27.1
Peak Deceleration	9.13g	6.4g

Exomars EDM 2016 values are corresponding to current status for industrial analyses and are reported as reference for MY24 scenario for a steep entry condition of -13.5 °

[1] EIP corresponds to 120 km altitude with respect to a reference equatorial radius of 3397.515 km

Tab. 2 provides a comparison of the MER-B and EDM entry scenarios in the region of Meridiani. Exomars is performing EDL roughly one our later than MER-B in the same area, for a season with 94° advance in solar longitude. EDM will present inertial entry velocities 190 to 310 m/s higher with respect to MER-B, which represents a relevant difference. The entry heading, as already evidences, is much more inclined wrt equator, with 118°÷125° heading with respect the 83° of MER. The orientation wrt posigrade eastwards entry is therefore only 7° for MER and is 28°÷35° for EDM.
The ballistic factor is more favorable for Exomars. At a reference mach number of 15, EDM will fly a 78 kg/m^2 wrt 88.9 kg/m^2 for MER.
Nose radius being 10% smaller and entry velocities 3÷5% higher, the heat fluxes are in any case expected to be larger even with similar entry flight path angles.

2.3 Arrival and Entry corridor

For the design of the sizing trajectories, in terms of thermal and mechanical loads, the entry scenarios within the allowable entry corridors has been scanned searching the cases maximizing the entry loads:

- Steep trajectory to be identified in order to cope with:
  - maximum heat flux, in order to select the TPS material and assess its suitability an qualification status
  - maximum deceleration loads

Tab. 3. Exomars 2016 Entry Descent and Landing Phases and Events.

PHASE/EVENT	BOUNDARIES	DURATION	DESCRIPTION - OPERATIONS
Pre-Separation	SEP-1h ÷ SEP	1h	IMU calibration
Separation	SEP	-	
Post-Separation	SEP÷ SEP + 2÷5m	2÷5m	INS mode navigation solution and data storage at hibernation start (state derivative and biases). State propagation from SEP+10m to HIBe+10m
Hibernation	SEP+2÷5m ÷ SEP+3d-1h (EIP-1h)	3d-1.3h	Hibernation start (HIBs) at SEP+2÷5m Hibernation end (HIBe) at EIP-1h
Post Hibernation	HIBe ÷ HIBe+35m	35m	Acc.bias and Gyro scale factor estimation; translational navigation + initialization at first step
Bridging	HIBe+35m ÷ HIBe+40m	5m	Acc.bias and Gyro scale factor estimation; translational navigation; rotational bridging (attitude reconstruction)
Pre-Entry	HIBe+40m ÷ EIP	20m	Acc.bias estimation; translational navigation; rotational navigation + initialization at first step
EIP	EIP	-	
Entry	EIP÷PAS	~178÷190s	Max laminar heating EIP+70÷84s Max g-load EIP+93÷100s
Parachute Deployment	PAS	-	EIP+178÷190s
Descent	PAS÷PAS+40s	40s	FSJ=PAS+40s. Current setting for separation below Mach 4. Possible need for timer reduction and higher Mach jettisoning for distancing in view of RDA operation
Front Shield Jettison	FSJ=PAS+40s	-	State perturbation for separation mechanisms activation.
Descent 2	FSJ÷FSJ+10s	10s	Descent with released front shield, FS distancing
RDAon	FSJ+10s = PAS+50s	-	Switch-on RDA RF channel
RDAok	2.5 km, ~RDAon+17÷40s	17÷40 s	RDA measurement acquisition and validation
Descent3	RDAok÷~2km		RDA converged, INS-terrain relative navigation hybridization, GNC computations for SP separation triggering
Pre-Separation	Down to 1.4÷1.0 km		Closed loop navigation, identification of SP separation triggering
SP Separation	SP-SEP	-	Triggering of separation
Free Fall	SP-SEP ÷ SP-SEP+1s	1s	Free Fall for SP distancing
RCS-on	SP-SEP+2s	-	Switch on RCS
GNC-on	SP-SEP+3s	1s	Closed loop control engagement. This phase duration to be confirmed wrt engines performance verification on cold start
Powered braking	SP-SEP+3s ÷ SP-SEP+33s	30s	Closed-loop g-turn and terminal braking
RCS-off		-	End-powered braking, terminal free-fall
Free-fall		1.0÷1.2 s	Free fall of SP, uncontrolled
Touch Down	SP-TD	-	Impact detection within E2E simulator, including DTM (slopes) and synthetic rock garden (random) and SP geometry/attitude

- maximum inflation loads for parachute design
- minimum deployment altitude, actually formulated in terms of verticalization requirement for the operation of RDA.

- Shallow trajectory to be identified in order to cope with:
  - maximum heat load for TPS sizing. The limit is artificially set to have heat loads within "reasonable" limits for TPS thickness sizing
  - minimum margin of 0.5° with respect to the shallowest entry angle to determine a skip entry
  - landing accuracy constraint

The design constraints for the identification of Entry Corridors are reported in Tab. 4. It is evidenced that two sets of requirements have been identified and iterated. On the left column (min corridor), an initial set of requirements has been defined for a nominal performance of the interplanetary navigation. On the column to the right (extended) a revised set of requirements is defined in order to implement the potential need of steeper entries required to cope with the poor performance of the interplanetary navigation (wrt MER arrival conditions) and the entry accuracy deterioration due to the need of separating EDM 3 days before nominal EIP.

The identification of the constraints has been performed taking into account a derivation procedure that had to be iterated during project phases, due to the relevant uncertainties brought in by the direct entry in dust storm scenario.

Landing area corresponds to MER-B (Opportunity) location, with intrinsically a different mission profile. Opportunity landed in the same region of Meridiani following a type-2 transfer, but with different arrival conditions, in particular for the entry heading.

The 3.3%÷5.5% higher entry inertial velocities are partially compensated by the smaller ballistic factor (78 vs 89 kg/m^2). The initial idea was therefore to fly similar entry flight path angles, -11.5° inertial (-12° co-rotating), thereby allowing potentially similar mission profile.

The initial "guess" had to be abandoned owing to the accuracy of the navigation solution, the estimation of the errors induced by the separation mechanism and the state covariance at the Entry Interface point which proved, at current maturity of the analyses, to be much worse than for MER..

The EDL constraints defined in Tab. 4 are therefore split in two columns, with the left one representing nominal values and the right one representing extended values that would be required in order to cope with more aggressive (steeper) entry dictated by landing accuracy.

The split is in line with the studies and recommendations raised as output of the Risk Analysis Working Group for the hyperbolic direct entry in dust storm conditions. For the specific topics related to risk mitigation in EDL phases the following points have been considered:

- Extend TPS material qualification level in order to increase the flight path to steeper entries, thereby reducing the increase of TPS mass brought in by the dust storm conditions (sizing case from both TPS thermal loads and parachute inflation loads), and to potentially decrease the landing dispersions
- Possibly reduce the arrival velocities from 3.25÷3.46 km/s to 3.0÷3.2 km/s with the some penalty in terms of propellant while performing Deep Space Maneuver (DSM), thereby allowing improvements in terms of both sizing loads and landing accuracy

The identification of the allowable peak heat fluxes, in lack of dedicated CFD's that have been run after the definition of the "sizing" trajectories, was defined relying on similarity from available data for hyperbolic entries , although performed during project history for different arrival velocities and seasons.

The cold atmospheric scenario is always the worst case in terms of convective heating. Owing to the low atmospheric densities at altitudes above the 45 km where peak heating is expected, deceleration is lower and relative velocities are higher, leading to maximization of the heat fluxes. In cold environment, transition from laminar to turbulent flow regimes has always been found (relying on ARD, Reda and Pant criteria) to occur close to the peak laminar heating condition predicted with the Sutton-Graves approximation.

From the set of dedicated CFD runs, the "scaling factor" of the turbulent fluxes expected on the corner with respect to Sutton-Graves cold wall approximation were in the order of 2.6. This led to the identification of the limit of SG heat flux as:

- 625 kW/m^2 for a Norcoat Liège[2] qualification limit of 1.6 MW/m^2 (achieved in Simoun arcjet facility in France, with comparison of Air-CO_2 test conditions)
- 780 kw/m^2 for a Norcoat Liège qualification limit raised to 2.0 MW/m^2 (to be achieved in Phase B2X2, corresponding approximately to the limit of Simoun facility in Air)

Mechanical loads have been raised consistently in order to allow extended steep entry window.

2.3.1 Entry Corridor Results

The evaluation of the entry corridors has been performed on the basis of the constraints outlined above, for the extreme velocity cases corresponding to

[2] Norcoat Liège is the light-weight ablating material selected for ExoMars Thermal Protection System (TPS)

the launch window start and end. Evaluation has been performed relying on an entry mass of 600 kg (BF 77.8 kg/m^2 at Mach 15), leading to the following results

- The corridor is maximum for the arrival corresponding to start of launch window, owing to the lower entry velocity: 2.87° wrt 2.49°
- The minimum guaranteed entry corridor of 2.49° for the whole missions scenario can only be achieved if the landing accuracy is not activated as a constraint, but is only taken as figure of merit. The shallowest entry with the heat load as only active constraint would lead to accuracies as bad as 200÷130 km. This huge error is in dominated by the accuracy at EIP, in terms mainly of fpa dispersion, coupled to shallow entries and long atmospheric flight. It can be seen that the shallow entries would lead to major axes of the landing ellipse in the order to 130÷195 km.
- Achieving 50÷60 km major axis landing accuracy with 1 deg corridor window cannot be currently demonstrated, but the improvements in the separation mechanism design and navigation solution for Trim Correction Maneuvers (TCM) implementation are promising towards the possibility of matching the required accuracy
- The accuracy at EIP is currently estimated to 22 km 3σ along track for a perfect Main Separation Assembly (MSA), that is raised to 28 km with 11 mm/s MSA lateral error at separation and 34 km with 29 mm/s MSA lateral error. The corresponding fpa accuracies are ±0.25°, ±0.35° and ±0.4° (3σ)
- Improvements in the navigation solution and TCM implementation, as well as re-design of MSA, is expected to improve the performance to at least 14 km (3σ) along track and less than 0.1° (3σ) fpa.
- The driving constraint from the steep entry standpoint is dominated by the verticalization requirement towards the usage of RDA following FS separation. Mechanical loads, parachute loads and heat flux constraint are only violated at steeper fpa's and do not represent active constraints.
- Current strategy is therefore to fly the steepest entry angles compatible with the expected flight path angle accuracy of ±0.4°. This leads, with the inclusion of some margin, to consider a minimum fpa corridor of 1° close to the steep limit. The implemented strategy allows coping with all constraints, while requiring a 130 km major axis of the landing ellipse. Expected improvements of the entry accuracy to ±0.3° and 25 km would lead to meeting 100 km major axis accuracy.
- The implication of the "long-tails" is evidenced in

Tab. 4. Entry Corridor Active Constraints

Parameter	Mild Constraint	Hard Constraint	Notes
Thermal Flux	<625 kW/m^2	<780 kW/m^2	Laminar heat flux constraint. Corresponds to turbulent overshoot below TPS (of 2.07 MW/m^2
Thermal Load	<37.0 MJ/m^2	<42.3 MJ/m^2	Shallow limit Heat Load Constraint (current sizing estimate in dust storm scer
Deployment Mach	1.6<Mach<2.1	1.8<Mach<2.1	Highest triggering window within the consolidated Mach±0.15 uncertainty thr triggering algorithm performance
Altitude at Deployment / Verticalization	>6.7 km	>6.7 km	Estimate with constraints under 12 m Huyghens DGB parachute and allocatec verticalization requirements Altitude losses allocation: - 1400 m for terminal braking with active RCS under 12 m DGB - 9.0 s for Radar Acquisition Phase - 5.0 s for GNC algorithms hybridization (INS+RDA) - 1.0 s for G-turn threshold detection - 2.0 s margin from back cover release and tip-off manoeuvre for g-turn a RDA requirements - 3000m±1000m: 55° off-vertical pointing - 2000m 35° max off-vertical pointing at 2000m
Load Factor	10.5g	12.2g	Extended steep entry case limit for the implementation of the hyperbolic entry EDL Risk Mitigation Working Group recommendations
Inflation Force	65kN	69kN	Extended steep entry case limit for implementation of the hyperbolic and dust Mitigation Working Group recommendations.
Landing Accuracy	100 km target 120 km const.	100 km target 120 km const.	Target to be achieved while keeping 3 days coasting from separation to EIP 120 km constraint for landing area morphology with current arrival azimuth
Minimum entry corridor	1.0 deg	1.0 deg	Minimum entry corridor compatible with flight path angle accuracy at EIP

the landing ellipses of Fig. 4. Large craters in the NW and SE areas would be a hazard to be check against sedimentary rock depositions in the surrounding areas.

- The identified corrective actions should in any case allow the reduction of the landing dispersions to include 120x16 km maximum landing accuracy compatible with Exomars mission ellipse orientation in Meridiani area.

Once the improvement in the navigation and separation performances will be demonstrated, the "mild" steep limits of the entry corridors may be met and long ellipse risks mitigated.

2.4 EDL Engineering Constraints

In order to allow successful entry descent and landing, as well as mission surface operations, some constraints shall apply to the selection of suitable landing sites.
These constraints are defined in terms of general characteristic related to the specific mission profile (interplanetary transfer, direct injection and coasting period, hibernation and pre-EDS wake-up), to the EDL operation (entry conditions and environment, safe operation of the descent system with parachute deceleration, controlled rockets braking, touchdown with crushable structure), to surface operations (thermal design) as well as communication constraints in order to allow direct tracking of critical EDL phases and communications to the Data Relay orbiter.

- Allowable latitude and longitude ranges
- Season and Local Time for EDL
- Upper limit for the landing region's altitude
- Landing ellipse 3-sigma dimensions and orientation
- Atmospheric parameters to cope with entry loads and required EDM performance
- Surface winds and vertical winds (katabatic / anabatic)
- Terrain Relief and Slopes
- Surface Rocks
- Terrain Radar Reflectivity and Thermo-physical properties

In the remainder, the definition of the above constraints is described with justification towards Exomars design status.

2.4.1 Terrain slope constraints

Terrain slopes mainly affect radar operation, GNC performance and terminal drop of Surface Platform on terrain.
At long base-lengths, in the order of kilometers, slopes affect the slant range measurements and thereby the altitude reconstruction. Radar switch-on is currently triggered of tuned lag timer with respect to the parachute deployment triggering, driven by a sophisticated g-switch and lag time based algorithm. Radar RF may be activated in altitude range 3÷6.5 km, but is operated in closed loop only below 2500 m AGL (unambiguous altitude measurements via suitable PRF tuning). The active constraint for slopes at 1 km base-length is 3 degrees.
At shorter base-lengths, in the order of 300 m, the major concern is related to engagement of the terminal descent phase, where a closed loop g-turn maneuver is initiated in order to cancel the vertical velocity as well as wind-drift horizontal velocity, with attitude correction to provide upright attitude at engines shut-down and surface platform touch-down. The terminal maneuver is performed at tuned vertical thrust-to-weight, with altitude extension depending on the terminal vertical velocities that are expected to be in a wide range variation due both to uncertainty in the atmospheric density in the last 2 km above ground level and to relevant turbulence expected when landing in the afternoon hours. Proper altitude-velocity estimation is therefore crucial in the altitude range below 2 km, and a constraint associated to 330 m base-length slopes has been identified in 8.6° in order to ensure proper fuel consumption – with margins - during powered descent.
The last constraint is related to the surface platform drop phase. In order to allow proper altitude release error for engines shutdown and final impact on

Tab. 5. Terrain Slope Constraints

Scale Length	Constraint	Rationale
2 to 10 km	Slope less that 3° on base-length of 2000m	Maximum error for radar slant range measurement. Radar may be activated in altitude range 3÷6.5 km, operated in closed loop below 2500 m (unambiguous altitude measurements via suitable PRF tuning
0.33 to 2 km		Bridging exponential self-affine model $C \cdot \Delta X^{(H-1)}$
330 m	Slope less than 8.6° on base-length of 330m	Ensure proper fuel consumption during powered descent
7 to 330		Bridging exponential self-affine model $C \cdot \Delta X^{(H-1)}$
<7m	Maximum relief 1.55 m down to maximum slope of 18°	Ensure proper altitude release error for engines shutdown and final impact on crushable structure

crushable structure, a maximum relief of 1.55 m has been identified as applicable on a base-length of 7m, corresponding to the maximum drift in free-fall associated to the worst case 2 m/s residual horizontal velocity.

2.4.2 Rock size and distribution constraints

Rock population is posing some relevant limitations on the performances of the crushable structure located below the surface platform. The crushable structure is designed to attenuate impact loads and at the same time to prevent overturn when touch down occurs on rocky terrain, potentially downhill, or with increased horizontal (parallel to terrain) velocities in case of uphill impact.

Current design of the crushable structure is to absorb the impact kinetic energy without inducing acceleration in excess of 30 g_E at any point, including payloads, for impact velocities up to 4.25 m/s and horizontal 0f 1.7 m/s and having a maximum rock height of 28 cm, which corresponds to the maximum rock size having 1% probability to be under the 2.14 m2 base area of the surface platform.

AS suggested from available literature on the subject, rock distribution is specified in terms of cumulative fractional area covered by rocks with diameter not larger than D, expressed as [1]

$$F_k(D) = ke^{-q(k)D} \qquad \text{(Eq.1)}$$

with rock abundance parameter k =0.069 applicable specification for Exomars, and q(k) = 1.79 + 0.152/k . The fractional area 0f 6.9% has been demonstrated a sounding worst case from IRTM measurement in Meridiani landing ellipse.

The cumulative number of rocks is computed considering the integration rule

$$N(k,D) = \frac{4}{\pi} \cdot \int_{\infty}^{D} \frac{dF}{D^2} \qquad \text{(Eq.2)}$$

The rock height-to-diameter ratio is defined as

$$H(D) = 0.5 \cdot D \qquad \text{(Eq.3)}$$

The probability of reaching no rocks of diameter larger than D or above within area A is then derived as

$$p_k(D,A) = 1 - e^{-N(D)\cdot A} \qquad \text{(Eq.4)}$$

As a derivation of the more general applicable long-tail Poisson law for the probability of finding exactly n rocks in area

$$p_k(n,D,A) = \frac{1}{n!}\left(N(D)\cdot A\right)^n e^{-N(D)\cdot A} \qquad \text{(Eq.5)}$$

2.4.3 Terrain Thermo-physical properties constraints

The thermo-physical properties of the terrain are bounded by the design of the Thermal Control System (TCS) that shall provide thermal conditioning of the electronic units of surface payloads for the required surface mission lifetime of 8 sols (8 nights) entirely relying on batteries.

Cold cases represent a driver, and therefore thermal inertia and albedo of the terrain at landing site shall meet specific constraints:

- Thermal inertia > 150 J m^{-2} $s^{-0.5}$ K^{-1}
- Albedo < 0.28

2.4.4 Radar reflectivity constraints

The ExoMars EDL design requires that the surface material present at the landing site be radar reflective and provide sufficient backscatter signal to enable measuring the altitude and velocity with respect to ground during the descent. The relevant constraints have been determined on the basis of realistic assessment of terrain reflectivity in the Meridiani area:

- Terrain Radar reflectivity > 0.07
- Backscatter cross section in Ka band (35 GHz) > -5 dB for nadir points, >-20dB for 80° off-nadir (Fig. 2, Hagfors model)

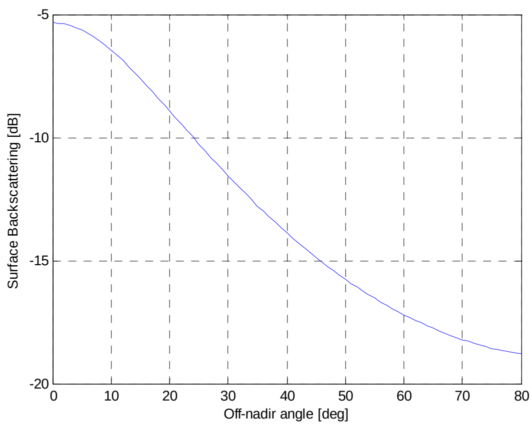

Fig. 2. Mars surface backscattering section Ka-band

3 TERRAIN ANALYSIS

Assessment of the terrain characteristics in the candidate landing area is mandatory in order to prove degree of compliance of the reference landing site to the outlined engineering constraints. During Exomars development phase methodologies are being developed to derive hazard maps based on available data products from Mars observation. Where coverage of the required area is not guaranteed, additional observations may be required to ESA-NASA orbiters in order to complete the process of characterization and certification of the safety for the selected landing site(s). For Exomars 2016 no Landing Site Selection (LSS) process will be set-up, since the target area is an Agency mission requirement. One possible alternative landing site will be identified, relying on EDL engineering constraints, in order to present a robust mission concept at System Preliminary Design Review (PDR) foreseen by the end of 2010.

3.1 Slope Characterization

As outlined in §2.4.1 slope constraints apply at kilometer (km), hectometer (hm) and meter (m) scale lengths, thereby requiring dedicated characterization for

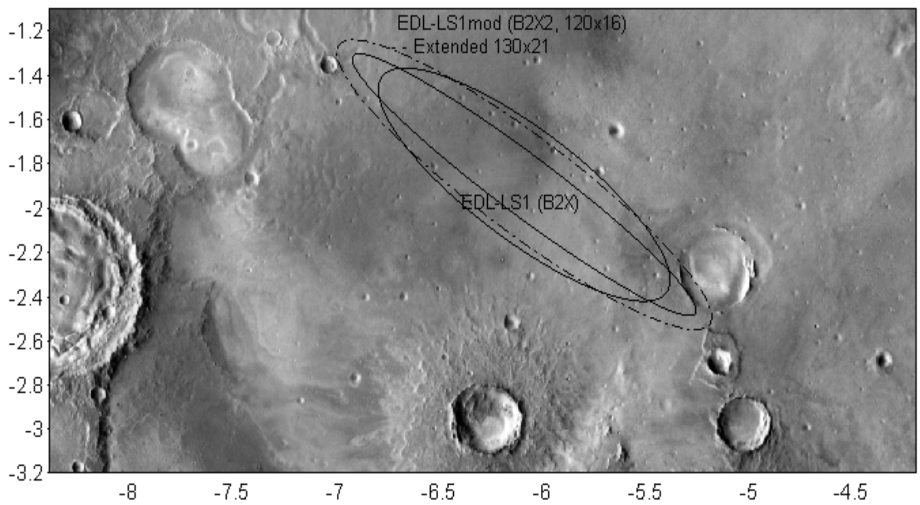

Fig. 3. EXM EDM Landing Accuracy. EDL-LS1 ellipses in Meridiani area.

The EDL-LS1 area considered in B2X has to be extended to cope with current uncertainties in entry delivery accuracy

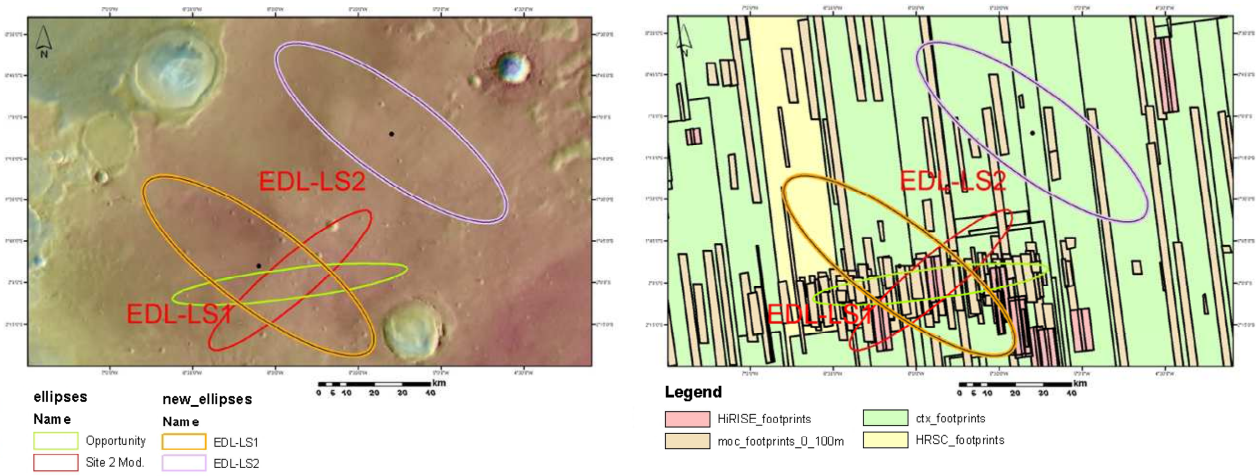

Fig. 4. Exomars 2016 Landing Ellipses and Image Coverage

The Exomars 2016 landing ellipses in Meridiani area are presented in the figure on the left with respect to Opportunity landing ellipse, Site 2 Mod represents the targeted ellipse for elder mission profile (posigrade entry from orbital release). EDL-LS1and EDL-LS2 represented the targeting ellipses for the new mission profile (retrograde direct entry).

The figure on the right presents the coverage from imaging at different resolutions. Full coverage of the Opportunity ellipse is evident, as well as the fact that large area of EXM ellipses has only coverage from CTX and HRSC. Only a couple of HiRISE stereo pairs is available the Region of Interest (RoI).

3.2 Derivation of Slope Maps

Slope constraints are defined in terms of adirectional slops, that can be derived from bi-directional slopes rebuilding from Digital Elevation Maps (DEM's) or direct measurement as for Photoclinometry.

The approach followed for Exomars is based on MOLA (463 m/pix) or HRSC (75 m/pix) data for the km and hm scales, and HiRISE/MOC/CTX (~1m/pix) for the metric scale, with the methodologies outlined in the following sections.

The extension of the slope maps that can be rebuilt largely depends on the availability of data for the RoI. Fig. 4 provides a synthetic plot of the coverage for Exomars Meridiani area of interest and expected landing ellipse. It is evident that the coverage of MER-B landing ellipse is rather complete (MOC footprints), while only a couple of stereo image pairs from HiRISE is available. The remainder of the area needs to be covered, at this stage, with HRSC or CTX footprints.

The techniques applied are therefore based on:

- Bi-directional slope determination from individual altimetry profiles (km-hm)
- Digital Elevation Maps creation from stereo images processing and slope data extraction, where images are available (m)
- Photoclinometry, basically derived from MOC images (m-hm)
- MOLA pulse-width at (hm)

3.2.1 MOLA Slope Maps

Mars Observer Laser Altimeter on Mars Global Surveyor (MGS/MOLA) allow retrieval of altimetric profiles from individual shots with horizontal resolution of 463 m, and is best suited for building DEM's at the km-hm scale length. Shots from MOLA are spaces 300 m along-track with 180md diameter, with accuracy of location in the order of 3 mrad horizontal and 10 m vertical. 600,000 shots are available in the MOLA measurement database, covering the whole planet, and 43 shots in the Exomars RoI (13 erroneous), for a total of 7449 shots. Bi-directional slopes have been derived relying of Lagrangian interpolation schemes as described in [3]. A-directional slopes are then derived relying on a Natural Neighbor interpolation algorithm as described in [4] for the rebuild of slopes at the required scale length. MOLA DEM's at 1km and 2km Baselength are shown in the upper plots of Fig. 5.

3.2.2 Photoclinometry

Photoclinometry (PC) or Shape From Shading (SFS) techniques can be used to infer surface topography from the brightness of an image. PC is complimentary to stereo because it uses a single image to produce slope maps and also elevation models of the surface at image pixel resolution.

Image brightness is related with the light energy captured from the imaging sensor. The flow of energy incident from the Sun on a planetary surface and reflected to the sensor is modelled by the Bidirectional Reflectance Distribution Function (BRDF). BRDF depends from incoming direction, local surface normal and outgoing direction. For Lambertian surfaces the emitted quantity of light is the same regardless of the outgoing direction, as a consequence pixel brightness can be used directly to compute the angle between local surface normal and the incoming direction. Slopes can also be used to determine a fit element model of the surface. There are three different kinds of PC algorithms that have been evaluated:

<u>0-dimensional PC</u>

It computes the local surface slope with respect to the areoid normal for each image pixel. 0-dim PC produces a slope map with the same footprint resolution of the processed image and intrinsically generates adirectional slopes

<u>1-dimensional PC</u>

Integrates the local slope along a given direction to produce an elevation profile.

<u>2-dimensional PC</u>

This approach uses a least square method to find the DEM that match best the image brightness. It requires an a-priori low resolution DEM to get initial conditions for the least square algorithm and to fix the final DEM scale factor.

Results from PC are sensitive to:

- Sun position and S/C position and attitude.
- Atmospheric scattering effects and haze.
- Albedo variations.

Each of these parameters must be considered in the PC analysis, which is very sensitive

3.2.3 HRSC products

Mars Express High Resolution Stereo Camera (MeX/HRSC) Lvel-4 products allow processing of stereo images with the resolution of 75m/pix, allowing vertical resolution up to 1m. HRSC images are typically rather noisy when used on very flat areas line Meridiani region

3.2.4 MOC products

Mars Global Surveyor Mars Orbiter Camera (MGS/MOC) allows processing with resolution >1.5 m/pix (3 m/pix typical). Stereo image processing implies complex calibration and processing

3.2.5 HiRISE products

Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (MRO/HiRISE) offers resolution >30 cm/pix (60 cm typical) allowing production of DEM's with 1 m resolution (~3 pixel). Over an estimated population of 1000 stereo-pairs, only a couple is available for processing in Meridiani area (Victoria crater region)

3.3 Radar reflectivity and Rock Distribution maps

Derivation of terrain radar reflectivity and backscattering of the Meridiani landing site is being performed in the frame of Environmental Terrain Support Analysis (ETSA) activities, in parallel to rock distribution, slopes and thermal properties characterisation. Impact of dust attenuation and related allowable limits in terms of 2-way signal attenuation have not been identified yet, and will be soon available with a parallel dust composition and distribution assessment, to be fed to Radar models to check compatibility and identify applicable constraints. Potential decrease of reflectivity Γ_0 to 0.045, based on current assessment of available measurements is under analysis, with potential additional losses below 1.5 dB.
Parallel activities are ongoing in order to complement preliminary rock maps, obtained from low resolution

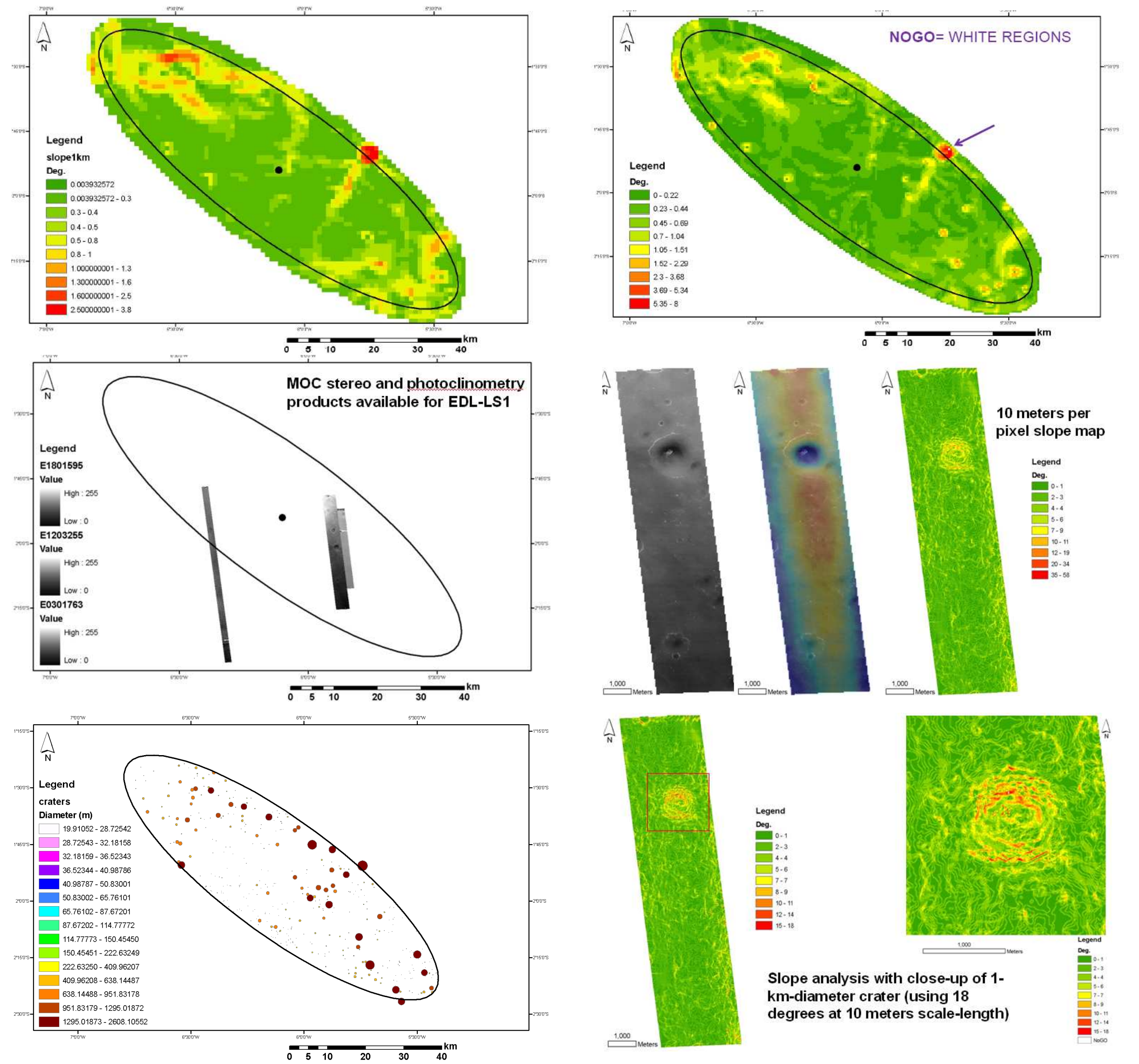

Fig. 5. Slope Analyses and Hazards close to crater rims

Km and hm slopes appear to pose no constraints for EDL (8°). Close-up to crater rims with dam scales shows areas with limited extension with slopes up to 18°. Up to 447 craters have been counted in the B2X ellipse footprint of 100x30 km thermal mapping from Viking InfraRed Thermal Mapper (IRTM). Thermal emission maps from Odissey THermal Emission Imaging System (THEMIS) and Mars Global Surveyor Thermal Emission Spectrometer (TES) have been used.

3.4 Limitation on landing ellipses due to preliminary terrain filtering

No major constraints have been identified from current characterization analyses from the standpoint of terrain constraints violation. Thermal inertia and albedo maps appear to be in line with engineering constraints (Thermal inertia > 150 $J \cdot m^{-2} \cdot s^{-0.5} \cdot K^{-1}$, Albedo < 0.28.

Slopes on the large scale hm÷km do not show relevant hazards, while the close-up to 10 m scale put in evidence hazards close to crater rims slopes exceeding 18° (and up to 58°).

A limited number of MOC stereo images is available so-far. Photoclinometry has been used for processing, and characterisation shall continue in phase B2X2 in order to identify risk rating based on crater distributions and fractional coverage of slope hazardous areas.

As far as rock distribution is concerned, processing of IRTM images led to the identification from thermal emission of rock abundance maxima up to k=0.069, which corresponds to VL1 specification. This extreme value led to the identification of the need to design crushable structure to be compatible with 0.38 m height for 1% probability of occurrence under the surface platform base area. This is clearly an extreme case, since large areas may be covered by less than 1% (k=0.01), as in the case of some portions of MER-B Opportunity landing area

MOC stereo and photoclinometry products available for EDL-LS1 will be complemented in Phase B2X2, by additional HiRISE and HRSC processing of available images, eventually to be complemented with additional imagery to be requested for areas identified as potentially critical around crater rims, as in the case of the subdued craters in the NW region of the extended ellipse (Fig. 4) and fresh craters in the SE region.

4 CONCLUSIONS

The specific configuration of Exomars 2016 arrival, related to the need of harmonization between EDL targeting in Meridiani area, monitoring of EDL events and acquisition of the final 74 degrees science orbit is posing some challenges for the landing ellipse.

The azimuth of the landing ellipse ranging 118 to 125 degrees, as well as its extension, determines the need of imaging of the target landing area in order to prove the degree of compliance of the selected area to the engineering constraints that apply for successful EDL demonstration.

The consortium led by TAS-I under ESA supervision is working to improve the capability in Europe to analyze, model and verify atmospheric and terrain characteristics that may affect success of the mission. The process of convergence of engineering constraints and characterization of the landing areas is in continuous evolution following the maturity of EDM design and the improvement in the characterization techniques, with the final target of providing a full certification of the suitability if primary (and back-up) landing sites for the fulfillment of Exomars 2016 EDM mission objectives.

5 ACKNOWLEDGEMENTS

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6 LIST OF ACRONYMS

AGL	Above Ground Level
ARD	Aerodynamic Reentry Demonstrator
BRDF	Bidirectional Reflectance Distribution Funct.
CFD	Computational Fluid Dynamics
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	ConText Imager
dam	decameter
DEM	Digital Elevation Map
DSM	Deep Space Maneuver
EDL	Entry Descent and Landing
EDM	EDL Demonstration Module
EIP	Entry Interface Point
ESA	European Space Agency
ETSA	Environmental Terrain Support Analyses
EXM	ExoMars
fpa	Flight path angle
HGA	High Gain Antenna
HiRISE	High Resolution Imaging Science Experiment
hm	hectometer
HRSC	High Resolution Stereo Camera
km	kilometer
LMD	Laboratoire de Metrologie Dynamique
MER	Mars Exploration Rover
MeX	Mars Express
MGS	Mars Global Surveyor
MOC	Mars Observer Camera
MOLA	Mars Observer Laser Altimeter
MRO	Mars Reconnaissance Orbiter
ODY	Odyssey
OM	Orbiter Module

PC	Photoclinometry
PRF	Pulse Repetition Frequency
RDA	Radar Doppler Altimeter
RoI	Region of Interest
SFS	Shape From Shading
TAS-I	Thales Alenia Space Italia
TCM	Trim Correction Maneuver
TCS	Thermal Control System
TES	Thermal Emission Spectrometer
THEMIS	THermal Emission Imaging System

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